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**6. AUTHORS**

J. P. Burke — UCSD
J. R. Zeidler — SSC San Diego

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

SSC San Diego
San Diego, CA 92152-5001

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| | | | | | **19B. TELEPHONE NUMBER** *(Include area code)* (619) 553-1581 |

# Increasing the CDMA Reverse Link Voice-Data Capacity Using a Per Rate Class Interference Method with Optimal Spatial Combining

Joseph P. Burke, *Student Member, IEEE*
Department of Electrical and Computer Engineering
University of California, San Diego
San Diego, CA 92093-0407
also with Qualcomm, Inc.
5775 Morehouse Drive
San Diego, CA 92121
email: jburke@qualcomm.com

James R. Zeidler, *Fellow, IEEE*
Department of Electrical and Computer Engineering
University of California, San Diego
San Diego, CA 92093-0407
also with SPAWAR Systems Center, D805
San Diego, CA 92152
email: zeidler@ece.ucsd.edu

*Abstract* - **The voice Erlang capacity is analyzed in a multi-antenna combined voice-data CDMA Reverse Link (RL). The influence of two different spatial combining techniques: Optimal Combining (OC) and Maximal Ratio Combining (MRC) on the voice Erlangs is evaluated when a single scheduled High Data Rate (HDR) data channel is shared by users desiring HDR services. The impact of randomly arriving data users on the voice Erlangs is also analyzed. A per rate class rise over thermal metric is defined and used with OC spatial combining. At large HDR values, increases in the voice Erlangs are illustrated when using OC vs. MRC.**

## I. Introduction

Wireless communications systems are evolving to provide HDR services to subscribers that demand them. New generations of Code Division Multiple Access (CDMA) systems provide technologies that offer a framework to support these combined voice and data services.

Optimizing these new CDMA systems to best support combined voice and data users is a challenging problem due to finite system capacity and different rate class Quality of Service (QOS) requirements: delay, outage probability ($P_{out}$), average data rate, and bit error rate. This creates a requirement to best utilize the finite resources to concurrently support the large number of low data rate (LDR) voice users and the small number of HDR users.

Employing a spatial antenna array with an interference suppression spatial combining algorithm (OC) is a method that has been proposed to increase the combined voice-data CDMA system capacity. In [1,2], large increases in RL capacity were demonstrated using OC spatial combiners for correlated fading antennas in scenarios with non-uniform clustering of users. [3] also illustrated large increases in RL system capacity using a Minimum Variance Distortionless Response adaptive combining algorithm via simulations with uncorrelated antennas.

Recent results in [4], however, contradict earlier results for spatial signal processing gains using OC vs. MRC on the CDMA RL. [4] analytically illustrated via RL Data Throughput that in a multi-cell RL system, the interference from users in neighboring cells significantly reduces interference suppression gains associated with OC vs. MRC.

In [4], the total received power to background noise ratio in the desired cell was constrained to meet system requirements (a common LDR system metric). We propose in this paper that a per rate class interference to background noise ratio method is the correct constraint to meet system requirements and should lead to increased spatial signal processing gains. We illustrate the difference between OC and MRC spatial combining by computing the voice Erlangs vs. Average Data Capacity for varying data user data rates.

A few HDR users with a large number of voice users strongly impacts the system $P_{out}$. [5] considered time scheduling of data users, compared to random admission, in a voice-data RL CDMA system and illustrated that a single HDR user or HDR *channel*, time scheduled among users desiring HDR services, maximizes RL Data Throughput. We recognize that a single HDR user or *channel* will also maximize the interference suppression gain associated with OC. This motivates us to compare (upper bound) OC and MRC spatial combining gains on the CDMA RL with a single scheduled HDR channel.

Section II describes the general system model in terms of power and interference. The motivation to schedule an embedded single HDR channel with OC spatial combining on the RL is discussed in Section III. Section IV describes a modified HDR RL and derives voice Erlang capacity.

## II. System Model

A per user multi-rate (mixed voice-data) power and interference distribution model for the CDMA RL is described in this section.

In order to focus on the different spatial combining techniques, a flat Rayleigh fading channel model, perfect average power control, perfect estimates of all parameters, and uncorrelated fading between antenna array elements are assumed.

### *A. Power Terms in the Reverse Link CDMA System*

We write the total received power at the receiver output of a Base Station RL as the sum $\sum_{i=0}^{K_t} P_i + I_{out}W + N_0W$ where $I_{out}$ is a noise power density (dBm/Hz) and $W$ is a noise power bandwidth (Hz). The total received power is comprised of the *in-cell* received power from all $K_u$+1 users, the *outer-cell* power from users in neighboring cells, and the background noise.

The total interference power, $I_oW$, at the receiver output for user *0* can be written as the total received power minus user *0*'s power:

$$I_0W = I_{in}W + I_{out}W + N_0W = \sum_{i=1}^{K_u} v_i E_b R_i + I_{out}W + N_0W \quad (1a)$$

$$= \sum_{i=1}^{K_u - 1} v_i E_b R_i + P_D + I_{out}W + N_0W \quad (1b)$$

where we have singled out a HDR user in (1b) with power $P_D$ and define: 1) $I_{in}W$ is the power of in-cell multiple access interference, MAI, from $K_u$ users where $v_i$ is the per user voice activity factor, $E_b$ the bit energy (energy/bit), and $R_i$ is the per user data rate (bit/sec), 2) $I_{out}W$ is the power of the MAI from all adjacent cells (multi-tier), and 3) $N_0W$ is the equivalent thermal noise power of the background noise and receive path signal conversion.

We define the other cell interference parameter, $f$, to be $f = I_{out}W / I_{in}W$ and define the rise over thermal metric as $\eta = N_0W / I_0W$ [6]. A typical value for $f$ = 0.55 and typical values for $\eta$ = 0.5 to 0.1 which correspond to $I_0/N_0$ ratios of 3 dB to 10 dB.

### *B. Number of LDR Users*

Defining a LDR user *slot* as the equivalent amount of power required to support a 9.6 kbps data user (voice activity factor $v$=1), we can calculate the $K_u$+1 number of LDR users or equivalent number of LDR *slots* that can be supported in a CDMA RL system:

$$\sum_{i=1}^{K_u} E_b R_i \le I_{in}W \quad or \quad \sum_{i=1}^{K_u} P_i \le I_{in}W$$

$$K_u \le K_0 = \frac{I_{in}W}{P_{LDR}} \quad (2)$$

where the power for each $i_{th}$ *slot* is equal to the average power per LDR user, i.e. $P_{LDR} = P_i = E_b R_{LDR}$.

## III. Motivation to Schedule a Single HDR User

We define the Outage Probability and illustrate that randomly arriving data users require more capacity than a single scheduled HDR user. This has the additional benefit of maximizing spatial combining gains using OC vs. MRC.

### *A. Randomly Arriving Voice and Data Users*

A Lost Call Held (LCH) relationship is used to model the probability that there are $K_u$+1 randomly arriving users on the system during a specified time duration (occupancy distribution) [6]. Each user on the system uses one of $K_0$+1 available *slots*. In the LCH model, arrivals of users on the system occur randomly at Poisson-distributed intervals with call service time per user assumed to be exponential.

Defining the total number of *slots* used by the voice, $X_V$, and data, $X_D$, users as $X_V + X_D = X_T$, the occupancy distribution, $P_k$, is defined as the probability that $X_T$, in time $t_1$-$t_2$, is equal to $k$.

Assuming independence of the two individual Poisson processes, the combined voice-data occupancy distribution, $P_K$, is the convolution of the individual voice only and data only occupancy distributions:

$$P_k = e^{-\left(\frac{v \cdot \lambda_V}{u_V} + \frac{\lambda_D}{u_D}\right)} \cdot \sum_{n=0}^{\infty} \frac{\left(\frac{\lambda_D}{u_D}\right)^n}{n!} \cdot \frac{\left(v \frac{\lambda_V}{u_V}\right)^{k-r \cdot n}}{(k - r \cdot n)!} \quad (3)$$

$$\text{subject to } k - r \cdot n \ge 0$$

Specific to each class, we define the arrival rate to be $\lambda$ (calls/sec) and call duration to be $1/u$ (seconds).

The outage probability is defined as the probability that the equivalent number of *slots* used by users in the system, $K_u$, is greater than the maximum slots allowed, $K_0$, for given system metrics.

$$P_{out} = \Pr\left(\sum_{i=1}^{K_u} v_i > K_0\right) = \sum_{K_0}^{\infty} P_k = 1 - \sum_{k=0}^{K_0} P_k \quad (4)$$

Supporting both voice and HDR data users in a LCH model can severely impact the voice only user capacity. The un-scheduled arrival of HDR data users on the system can statistically at times use most of the available RL Capacity. Scheduling the HDR user, however, ensures the relative amount of system capacity used by the HDR user is well defined and a minimum desired voice only capacity is maintained.

Fig. 1 illustrates $P_K$ for $K_0$=26, $Pout$=1%, $v$=3/8, $\lambda_V/u_V$=10, $\lambda_D/u_D$=0.75, $R_V$=9.6 kbps, and $R_D = 8 \cdot R_V$ in a two antenna system with $\eta$=0.25, $f$=0.55, and $Eb/Io$=4 dB. The HDR traffic significantly influences the shape of $P_K$ as seen via the multi-modal PDF in Fig. 1-b.

### *B. Single HDR User Maximizes Data Throughput*

In a multiple access scenario on the CDMA RL, while employing mixed voice-data communications, one dominant high data rate user will allow for the highest total RL Data Throughput [4,5].

In a multi-rate system with a HDR user, the HDR user's own power is coherent to itself, per multi-path, and can be an appreciable part of the total receive power. Hence, the HDR user will experience a lower total interference. Targeting the same final Eb/Io (same frame error rate), a decreased interference will after power control yield a decreased power used per user for an expected data rate.

*C. Single HDR User Maximizes OC Spatial Processing Gains*

Specifying in a system a set amount of power to be allocated for data users, maximum OC vs. MRC gains are realized when interference is located in a single spatial vector direction. LDR users in the system will obtain greater OC spatial gains with a single HDR user than with multiple medium data rate users having the same total power as the HDR user.

The average value of Z, the gain using OC vs. MRC, was derived in [7] and found to be dependent upon $m$, the number of antennas, and $c^2 = \sigma^2/\sigma_y^2$, the ratio of the background noise power to HDR user signal power.

Z for a single HDR user was defined as:

$$Z(m,c^2) = 1 + \frac{(m-1)}{c^2(m+1)!} \cdot \left( \begin{array}{l} \sum_{r=0}^{m} (-1)^r (c^2)^r (m-r)! + \\ + (-1)^{m+1} (c^2)^{m+1} \exp(c^2) Ei(1,c^2) \end{array} \right) \tag{5}$$

where $Ei(n,x) = \int_1^{\infty} \frac{\exp(-x \cdot t)}{t^n} dt$. Note that $A$ in Section IV is inversely proportional to $c^2$, i.e. $A = \frac{1}{c^2} = \frac{\sigma_y^2}{\sigma^2}$.

## IV. MODIFIED HDR REVERSE LINK SYSTEM

In this section we discuss a modified RL with a single HDR user with OC spatial combining that allows for an increased $I_{in}W$.

### *A. Specifying System for HDR User and LDR Total Interference with Z*

The discussion in the previous section motivates us to define a modified CDMA Reverse Link system whereby:

*1) A single HDR channel is scheduled and shared by multiple users desiring HDR services.*

*2) LDR users follow a LCH model.*

*3) OC Spatial Combining is used to exploit high degrees of spatial coloring from the HDR user. Interference suppression gains using OC vs. MRC are realized on the HDR user in the desired cell.*

*4) Equally loaded cells with HDR users present in surrounded cells are assumed. HDR users in other cells are assumed to not offer interference suppression using OC.*

*5) The total system allowable Receive Power rise over thermal metric is replaced with a per rate class allowable receive interference rise over thermal metric. Each data class must meet it's specified receive interference rise over thermal metric.*

Note, similar to current CDMA RL system design, each users power control algorithm operates in the presence of the *realizable* interference seen by that particular user.

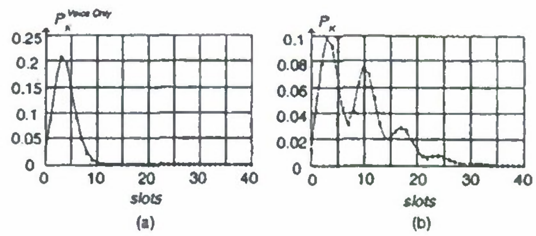


Fig. 1. $P_k$ vs. Number of LDR slots for a Randomly Arriving Voice and Data User System: (a) Voice only PDF, (b) Combined voice-data PDF.

### *B. Rate Class Interference Rise Over Thermal Discussion with OC Spatial Combining*

$P_D$ is defined to be a multiple of the non-HDR user interference power in the system to support a set HDR user data rate. Referencing notation in [4] and substituting $A=\kappa$ we define $A$ to be the ratio of the data user's power to the total interference minus the data user's power:

$$A = \frac{P_D}{I_0 W - P_D} = \frac{P_D}{I_{in}^{LDR} W + I_{out} W + N_0 W} = \frac{P_D}{I_{TOT}^D W} \tag{6}$$

with $A$ times the data user's processing gain ($G_D = W/R_D$) being equal to the data user's $E_b^D / I_{TOT}^D = E_b^D / I_0^{HDR} = A \cdot W/R_D$.

$P_D$ can be described as:

$$P_D = \frac{E_b^D / I_0^{HDR}}{E_b^D / I_0^{HDR} + W/R_D} \cdot I_0 W \tag{7}$$

We write the LDR only in-cell interference power $I_{in}^{LDR} W = I_{in} W - P_D = \sum_{i=1}^{K_v - 1} v_i E_b R_i$ and re-write the total received interference power (1) as:

$$I_0 W = \left( I_{in}^{LDR} W + I_{out} W + N_0 W \right) \cdot (1 + A) \tag{8}$$

Often the total received power and the total interference power to the LDR user are used interchangeably when describing $\eta$ and the maximum number users supported in a system. However, in a multi-rate RL using OC spatial combining a per rate class $\eta_R$ is needed.

Realizing that OC spatial combining will suppress the HDR user's power, $P_D$, by $Z(m,1/A)$, we write the interference using OC to the LDR users as:

$$I_0^{LDR} W = \left( I_{in}^{LDR} W + I_{out} W + N_0 W \right) \cdot \left( 1 + \frac{A}{Z(m,1/A)} \right) \tag{9}$$

where $I_0 W \ge I_0^{LDR} W$ such that we now desire:

$$N_0 W = \eta I_0^{LDR} W \tag{10}$$

Realizing that LDR users do not color the spatial interference enough to obtain OC gains vs. MRC, we write the interference to the HDR as:

$$I_0^{HDR}W = I_{in}^{LDR}W + I_{out}W + N_0W \quad (11)$$

When $P_D \geq P_V$, then $I_0^{HDR}W \leq I_0^{LDR}W$ and meeting the rise over interference metric for the LDR user class will ensure the rise over interference metric for the HDR user class is also met:

$$If \quad \eta \cdot I_0^{LDR}W \leq N_0W \quad then \quad \eta \cdot I_0^{HDR}W \leq N_0W \quad (12)$$

In general and on average, a user in the lowest rate class of all users will experience the greatest interference and hence will be of the class of users that limits the system capacity via an interference rise over thermal metric.

### *C. Increasing $I_{in}$ with Spatial Antenna Array Processing*

In this section we derive the increase in $I_{in}^{LDR}W$ using OC versus increasing $P_D$ via $A$.

$I_{out}W$ is derived from a multi-tier neighboring cell interference architecture each composed of a HDR user and many LDR users. We assume the affect of the many neighboring cells is to spatially whiten $I_{out}W$. Hence, we do not model $I_{out}W$ with benefit from interference suppression gains using OC:

$$\begin{aligned} I_{out}W &= f \cdot \left[ I_{in}^{LDR}W + P_D \right] \quad (13) \\ &= f \cdot \left[ I_{in}^{LDR}W + A \cdot \left( I_{in}^{LDR}W + I_{out}W + N_0W \right) \right] \end{aligned}$$

Rearranging (13), we obtain $I_{out}W$ as a function of $I_{in}^{LDR}W$, $N_0W$, and $A$:

$$I_{out}W = \frac{[1+A] \cdot f \cdot I_{in}^{LDR}W + f \cdot A \cdot N_0W}{1 - f \cdot A} \quad (14)$$

We substitute (10,13) into (9) to obtain $I_{in}^{LDR}W$ as a function of $A$ and $I_0^{LDR}W$:

$$I_{in}^{LDR}W = I_0^{LDR}W \cdot \left( \frac{1 - f \cdot A}{1 - A \cdot Z(m, f \cdot A)} - \eta \right) \Big/ (1+f) \quad (15)$$

(15) allows us to write the total Reverse Link System Throughput, *RLT*, from [4] as:

$$\begin{aligned} RLT &= K_0^{LDR} \cdot R_{LDR} + R_{HDR} \quad bps \quad (16) \\ &= \left[ \frac{\left( I_{in}^{LDR}W / I_0^{LDR}W \right)}{\left( E_b R_V / I_0^{LDR}W \right)} + 1 + \frac{A \cdot W}{E_b^D / I_0^{HDR}} \cdot \frac{1}{R_V} \right] \cdot R_V \quad bps \end{aligned}$$

Fig. 2 illustrates RLT using OC and MRC vs. the HDR user's data rate using (16). Using the rate class interference rise over thermal metric described in Section IV-B, we see an increased in OC RLT vs. that previously reported in [4].

### *D. Scheduled Data User and Randomly Arriving Voice Users Using OC*

Scheduling the HDR user simplifies (3) to that of the voice only Poisson distribution:

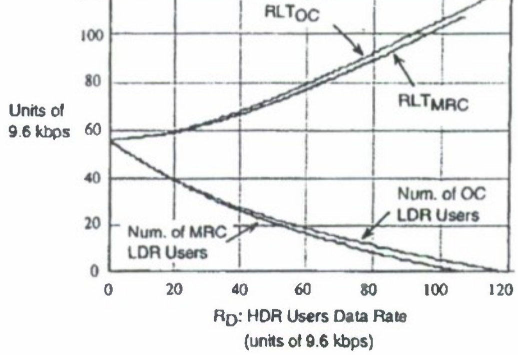


Fig. 2. Reverse Link System Throughput, RLT, and Number of LDR Users for a $m$=4 Antenna System and One HDR user: $\eta$=0.25 and $f$=0.55, *Eb/Io*=0.5 dB.

$$P_k^{Voice} = e^{-\frac{\lambda_V}{u_V}} \cdot \frac{(\lambda_V / u_V)^k}{k!}$$

The impact on the outage probability in (4) is that a smaller number of *slots*, $K_0^{'}$, are offered to support a smaller number of $K_u^{'}$ LDR users as the HDR user uses up a portion of the available $I_{in}W$.

$$P_{out}^{LDR} = \Pr\left( \sum_{i=1}^{k_u} v_i > K_0^{'} \right) = \sum_{K_0^{'}}^{\infty} P_k^{Voice} = 1 - \sum_{k=0}^{K_0^{'}} P_k^{Voice}$$

Using (2,7), we can describe allowable $K_0^{LDR}$ for a given $R_V$ versus $R_D$ to determine the voice only Erlangs as a function of $R_D$. The allowable number of LDR slots, $K_0^{'}$, using OC and a single scheduled and shared HDR channel can be described as:

$$\sum_{i=1}^{K_u^{'}} P_i \leq I_{in}^{LDR}W \quad \text{such that} \quad K_U^{'} \leq K_0^{'} = \frac{I_{in}^{LDR}W}{P_{LDR}}$$

Fig. 3 and Fig. 4 illustrate voice Erlangs vs. the Average Data Capacity. The Average Data Capacity is defined as: 1) for randomly arriving data users this is the normalized data rate times the average number of calls, 2) for single scheduled data user this is the normalized data rate.

Fig. 3 illustrates the voice Erlangs for m=2 antennas and different number of data rates. The curve for $R_D = 1 \cdot R_V$ is comparable to the dual class Erlang capacity analysis in [8]. Higher rate randomly arriving data users, beginning at data rates of $R_D = 16 \cdot R_V$, illustrate a significant non-linear perturbation to the combined $P_K$ or voice Erlangs (multi-modal $P_k$ PDF). Scheduling the data user, we obtain a higher voice Erlang metric than for randomly arriving data users, with maximum voice Erlangs obtained with OC spatial combining.

The results in Fig. 3 illustrate that randomly arriving data users whose data rate requires a significant percentage of the total system capacity greatly reduces overall system data throughput. Combinations of technologies that reduces the discrete influence of a higher rate users: more antennas, OC spatial combiners, etc. in addition to scheduling of the data user is therefore desirable.

Fig. 4 illustrates the voice Erlangs for m=4 antennas. Randomly arriving data users at $R_D = 16 \cdot R_V$ are more easily accommodated. Significant non-linear perturbation to the combined voice-data $P_K$ can be seen with $R_D = 32 \cdot R_V$. Increased gains are also realized using OC vs. MRC for the scheduled HDR channel.

## V. CONCLUSION

The OC vs. MRC gains determined in [7] were used to calculate the increase in voice Erlang capacity with a single HDR scheduled and shared channel in a CDMA multi-rate multi-antenna Reverse Link system.

Increasing the Reverse Link system capacity through an increased number of antennas reduces the non-linear impact of HDR users on $P_K$ for a specified data rate.

Scheduling the data users allowed a minimum voice only Erlang capacity to be maintained while OC spatial combining offered at large HDR values a trade-off between increased HDR traffic or voice Erlangs.

Realizing in Fig. 3 and Fig. 4 that at large HDR values the amount of Erlangs for voice is low, small changes in the HDR power will have significant affects on the voice Erlangs. Using OC vs. MRC and the per rate class rise over interference metric, we observed 12.8% increase in voice Erlangs for m=2 with $R_D = 32 \cdot R_V$, a 16.6% increase in voice Erlangs for m=4 with $R_D = 64 \cdot R_V$, and a 90% increase in voice Erlangs for m=4 with $R_D = 96 \cdot R_V$. We note, however, that imperfect power control, frequency selective fading, and finite mobile transmit power will in practice limit true realizable gains relative to these theoretical maximum.

Purposefully operating a CDMA Reverse Link system with highly colored interference via a common shared and scheduled HDR transport channel while using OC spatial combining and the per rate class interference metric offers a measurable increase in voice Erlangs.

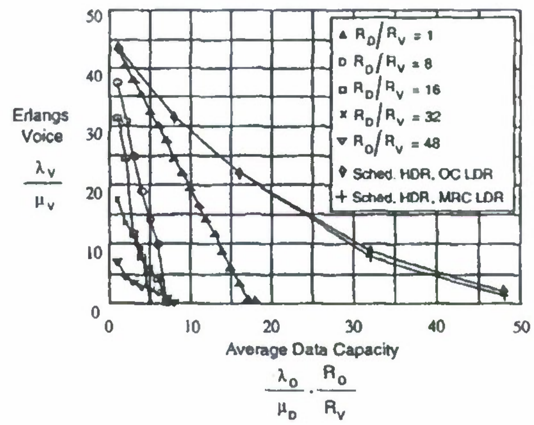


Fig. 3. Voice Erlangs vs. Normalized Average Data Capacity: $m$=2 antennas, $K_0$=26, $Pout$=1%, $\nu$=3/8, $R_V$=9.6 kbps, $\eta$=0.25, $f$=0.55, and $Eb/Io$=4 dB.

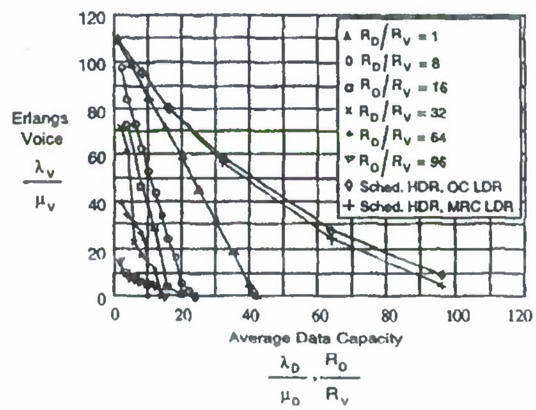


Fig. 4. Voice Erlangs vs. Normalized Average Data Capacity: $m$=4 antennas, $K_0$=56.5, $Pout$=1%, $\nu$=3/8, $R_V$=9.6 kbps, $\eta$=0.25, $f$=0.55, and $Eb/Io$=0.5 dB.

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